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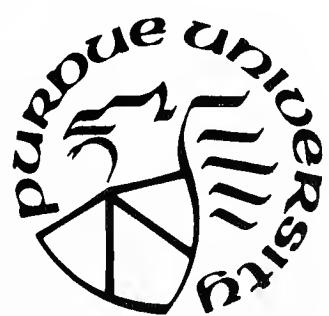
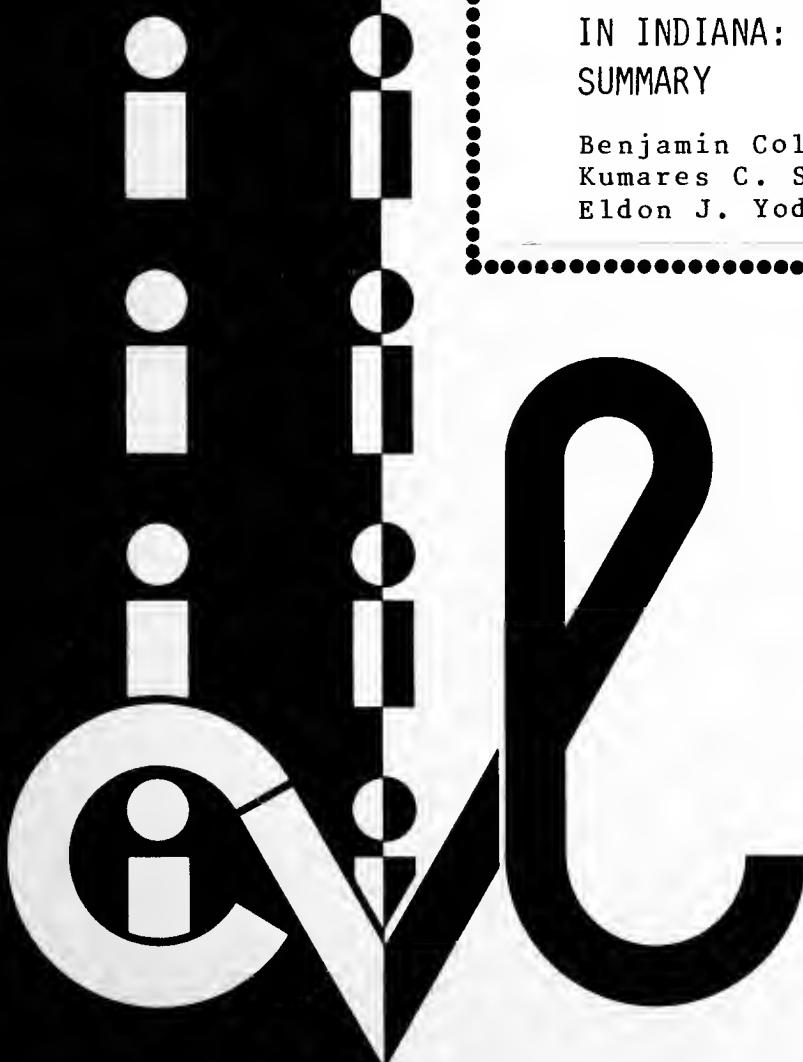
INDIANA
DEPARTMENT OF HIGHWAYS

JOINT HIGHWAY RESEARCH PROJECT

FHWA/IN/JHRP-84/10, Vol. I

DEVELOPMENT OF A METHOD FOR
ESTABLISHING RESURFACING PRIORITIES
FOR THE PAVEMENT MANAGEMENT SYSTEM
IN INDIANA: VOL. I - EXECUTIVE
SUMMARY

Benjamin Colucci-Rios
Kumares C. Sinha
Eldon J. Yoder



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Final Report

DEVELOPMENT OF A METHOD FOR ESTABLISHING RESURFACING PRIORITIES FOR THE PAVEMENT MANAGEMENT SYSTEM IN INDIANA

TO: H.L. Michael, Director
Joint Highway Research Project July 3, 1984
 Revised May, 1985

FROM: K.C. Sinha, Research Engineer
Joint Highway Research Project Project: C-36-63I
 File: 9-7-9

Attached is the Final Report on the HPR Part II Study entitled, "Development of a Method for Establishing Maintenance Priorities for the Pavement Management System in Indiana." The research was conducted by Mr. Benjamin Colucci-Rios under the direction of Professors K.C. Sinha and E.J. Yoder.

The report here documents the data used, the procedures followed, the models developed, and model results. Recommendations for incorporating the study findings in the IDOH Pavement Management System are also included. It should be noted that the study findings have already been presented to the members of the IDOH Pavement Management Task Force by Mr. Colucci and Professor Sinha in a workshop held on May 7, 1984.

The report contains three volumes; Vol I provides an executive summary, Vol II presents the study procedures and results, and Vol III includes the appendices.

This report is forwarded for review, comment and acceptance by the IDOH and FHWA as fulfillment of the objectives of the research.

Respectfully submitted,

K.C. Sinha
Research Engineer

KCS/jaj

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Final Report

**DEVELOPMENT OF A METHOD FOR ESTABLISHING RESURFACING
PRIORITIES FOR THE PAVEMENT MANAGEMENT SYSTEM IN INDIANA
VOL. I: EXECUTIVE SUMMARY**

By

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Joint Highway Research Project

**Project No.: C-36-63I
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Prepared as Part of an Investigation

Conducted by

**Joint Highway Research Project
Engineering Experiment Station**

**Purdue University
in cooperation with the**

Indiana Department of Highways

and the

**U.S. Department of Transportation
Federal Highway Administration**

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views of policies of the Federal Highway Administration. This report does not constitute a standard, specification or regulation.

**Purdue University
West Lafayette, Indiana**

July 3, 1984

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16. Abstract <p>This document is the executive summary of the research conducted by the Joint Highway Research Project of Purdue University in cooperation with the Indiana Department of Highways on the development of a method for establishing resurfacing priorities for the pavement management system in Indiana.</p> <p>The first part of the project included a review of the pavement management concepts including a description of existing pavement management practices. In the second part, the performance factors related to pavement deterioration were identified and the methodology used for developing equivalent performance indices (EPI) for each performance factor was defined. The third part involved the details pertaining to the two pavement condition surveys conducted. The fourth part included the development of a methodology for constructing a performance function model. The fifth part of the project involved the development and application of two optimization models for the Indiana interstate highway network.</p>			
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INTRODUCTION

Most of the state highway departments across the nation are in need of a rational method that can provide them with the number of deficient miles that can be rehabilitated with the limited resources available in any given year. In particular, these agencies are interested in identifying the exact location and length of those pavement sections of a given highway class which are in need of immediate attention including the type of most cost-effective rehabilitation activity during a given period of time. The use of optimization techniques appears to be a viable solution for this critical problem.

This report is an executive summary of the final report of a project conducted by the Joint Highway Research Project of Purdue University in cooperation with the Indiana Department of Highways on the development of optimization approaches for the pavement management system in Indiana [1]. This report describes a methodology, based on a zero-one integer programming technique, for establishing resurfacing priorities at the network level that can be incorporated in a pavement management system of any state highway agency. The optimization schemes use the paving contract section as the unit that represents the decision variable. The mathematical model takes into account pavement condition, present roughness, increase in roughness over time, and traffic. Different types of resurfacing activities are also incorporated into the mathematical model. A performance function model that relates resurfacing strategies with the overall reduction in pavement roughness present in the pavement section just prior to resurfacing is also presented in the report.

The optimization model has the capability to consider deficient pavement sections at any point in time within the analysis period specified. The

impact of different budget scenarios is also discussed in the report. The method in which the model selects the pavement sections and resurfacing strategy combinations that achieve an optimal resurfacing program during a given five year planning horizon is described using the Indiana interstate highway network data base.

OVERVIEW OF PAVEMENT MANAGEMENT

A review was first made of the concepts and definitions of pavement management. Then the pavement management programs followed or developed by the following agencies including state and provincial highway departments were examined in detail:

- Alberta
- Arizona
- California
- Colorado
- Construction Engineering Research Laboratory, U.S. Army
- Denmark
- Florida
- Idaho
- Illinois
- New York
- Ohio
- Ontario
- Pennsylvania
- South Dakota
- Texas
- Utah
- Washington

The review included a detailed examination of the methods used by these agencies to measure roughness, surface condition, structural adequacy, and surface friction.

IDENTIFICATION OF PERFORMANCE INDICATORS

The performance indicators evaluated in this research study are listed

below:

1. Current Directional ADT
2. Accumulated ADT
3. Present roughness number
4. Change in roughness number between years
5. Pavement Condition Index (PCI)
6. Pavement Age

Pavement thickness was not considered since it was assumed that pavements in service were designed for the loads which are actually imposed on them. In addition, it was felt that the relative weight assigned to this factor might not make a significant difference in the overall ranking of the contract section being considered. The South Dakota DOT includes pavement thickness as one of the factors in priority setting procedure. However, the relative weight assigned to it is actually less than 5 percent of the total weight assigned to the performance elements considered by the state [9].

The ADT was used as a surrogate for the Equivalent Axle Load (EAL) and Accumulated EAL for several reasons. First, at the present time Indiana does not collect truck weight distribution data on the Federal-aid secondary system. Even though an approximate estimate can be made based on data from weigh stations opened in the past, which is in the range of .30 to .40 EAL per truck, it was felt this number might just be a constant factor applied to every Federal-aid secondary road considered in the model, and thus would not change the final results of the optimization model.

The percent trucks is also considered a good indicator. However, this

information was available from only 28 permanent stations as reported in the 1981 IDOH Traffic Statistics report [2].

For the reason discussed above and at the suggestion of the IDOH, the present study included the current ADT as well as the accumulated ADT of each pavement section rather than EAL and accumulated EAL. The information on ADT was available for every pavement contract section considered in the study.

The effect of climate was not considered since it was assumed that pavements were designed for the environmental effects of the geographical region in question. The problems associated with severe climatic conditions are indirectly taken into account in the pavement condition index which is one of the factors considered in this study.

Friction and change in friction number were not considered for several reasons. First, based on the literature review, some of the states which have implemented pavement management programs, such as Florida and California [10], felt that friction plays a role only in those cases where the friction number is below a pre-determined value, say less than 30. In fact, it is required in Indiana that every pavement section should have a surface with anti-skid properties. Therefore, if during any fiscal year there is a pavement section with a friction number less than 30, irrespective of how rough is the pavement section or the magnitude of the distresses encountered, an immediate action is mandated. The South Dakota DOT takes friction into account in priority setting procedure, however, the weight assigned to this factor is only 3 percent [9].

Pavement deflection was not considered in this study. The IDOH does not collect deflection data on a routine basis. Nor is there any future IDOH plan to collect state-wide pavement deflection measurements. In fact, at present

only one of the states (Utah) that have developed pavement management systems at the network level, actually collects deflection data on a routine basis [10].

Drainage was not considered in this study, since the IDOH does not collect detailed drainage data on a routine basis for the entire highway network.

At this stage, the question can be raised as to how state highway agencies can analyze and evaluate the performance factors in the most efficient and cost-effective manner so that the information can be useful in pavement rehabilitation decision making process. Ideally, this can be accomplished if, in fact, the state can predict, from the roadway inventory and from the above factors, which pavement sections need immediate repair action as compared to those pavement sections which can still provide an acceptable performance in the years to come.

Decision to Use Pavement Contract Section

After the performance factors were chosen, it was necessary to decide what unit of measurement best represents the current condition of any highway segment. The state of Arizona, for example, divides the highway network into 7,400 one-mile segments [3]. The normal practice, however, is to use the paving contract section as the smallest unit of measurement. In Indiana, the pavement contract section is used as the unit of measurement since pavement characteristics such as pavement thickness, age, width, drainage, materials, construction method, etc. are, in most cases, homogeneous throughout the entire section. Previous research projects conducted at Purdue University have shown that the paving contract section is the best experimental unit to be used in a comprehensive pavement evaluation system [4,5].

Decision to Use Milepost Number

One of the major items necessary for successful implementation of any pavement management program is the ability to associate all performance data to a common reference point. The milepost number seems to be a very good indicator for analyzing all the performance factors previously described.

For example, every characteristic of interest to the state can be projected visually on a two-dimensional graph where the performance factor associated with each highway contract section is plotted in the vertical axis and the corresponding milepost number in the horizontal axis. Figures 1 and 2 show graphs of Roughness Number and Increase in Roughness Number against milepost number for Interstate 64 east during 1981. The type of pavement is also included in the graph. Each pavement contract section is represented by a horizontal segment enclosed within each consecutive pair of observations. Based on Figure 1 it can be noted that the only significant rough spot in Interstate 64 East is a concrete pavement section located about 125 miles east of the Illinois-Indiana State Line. This contract section is about 0.4 mile long and the roughness number is close to 3000 counts per mile. With the exception of this pavement section, the roughness numbers along this route are quite uniform ranging between 500 and 1500 counts per mile throughout the entire segment.

In Figure 2 it can be noted that the increase in roughness number in Interstate 64 East is, in most cases, between 0 and 300 counts per mile. It is interesting to note that the pavement section which had a very high roughness number on Figure 1 is also deteriorating at a very high rate since the increase in roughness number experienced between 1979 and 1981 is in the range

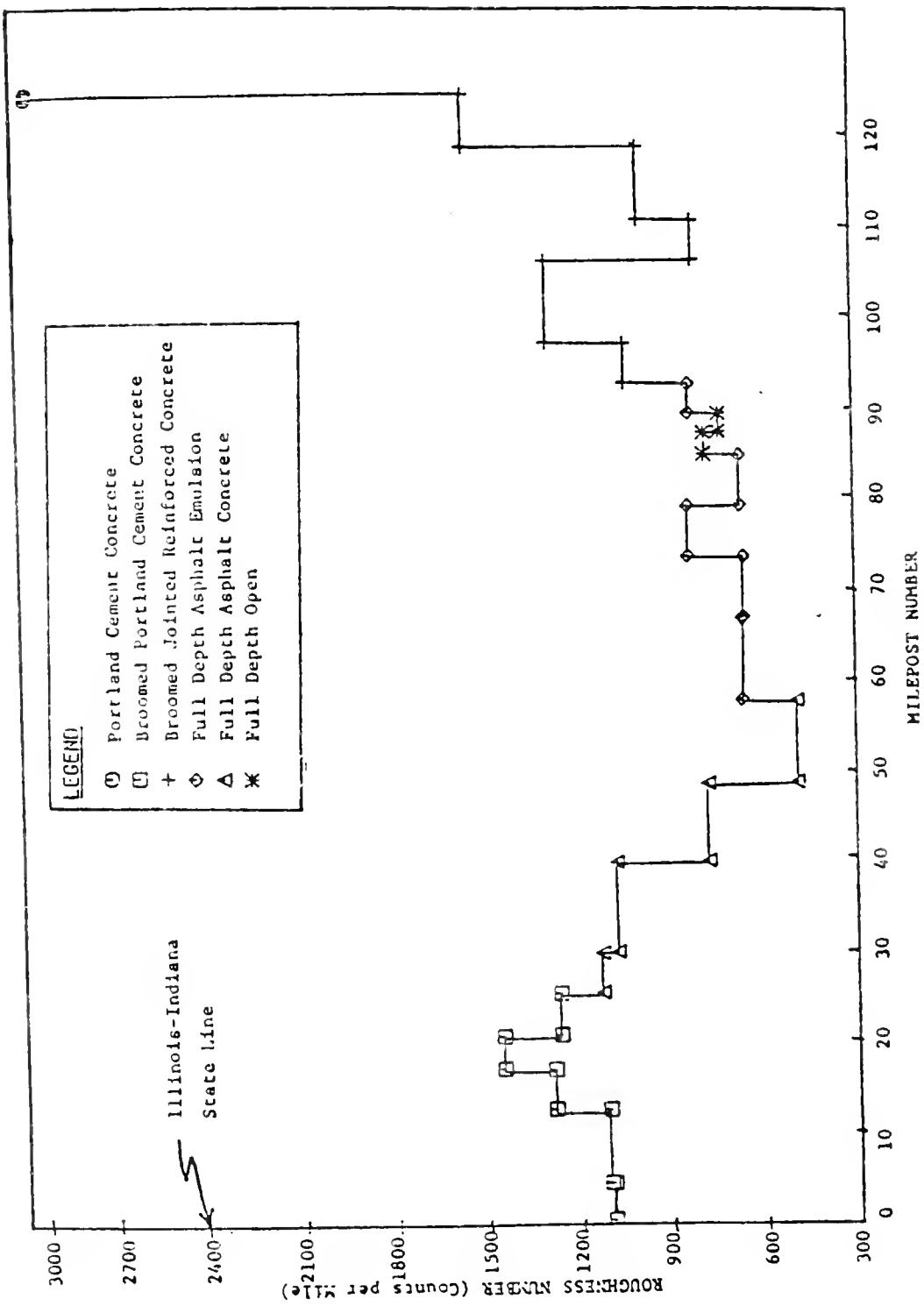


Figure 1. Roughness Number vs. Milepost Number for I-64 East (Indiana) during 2001.

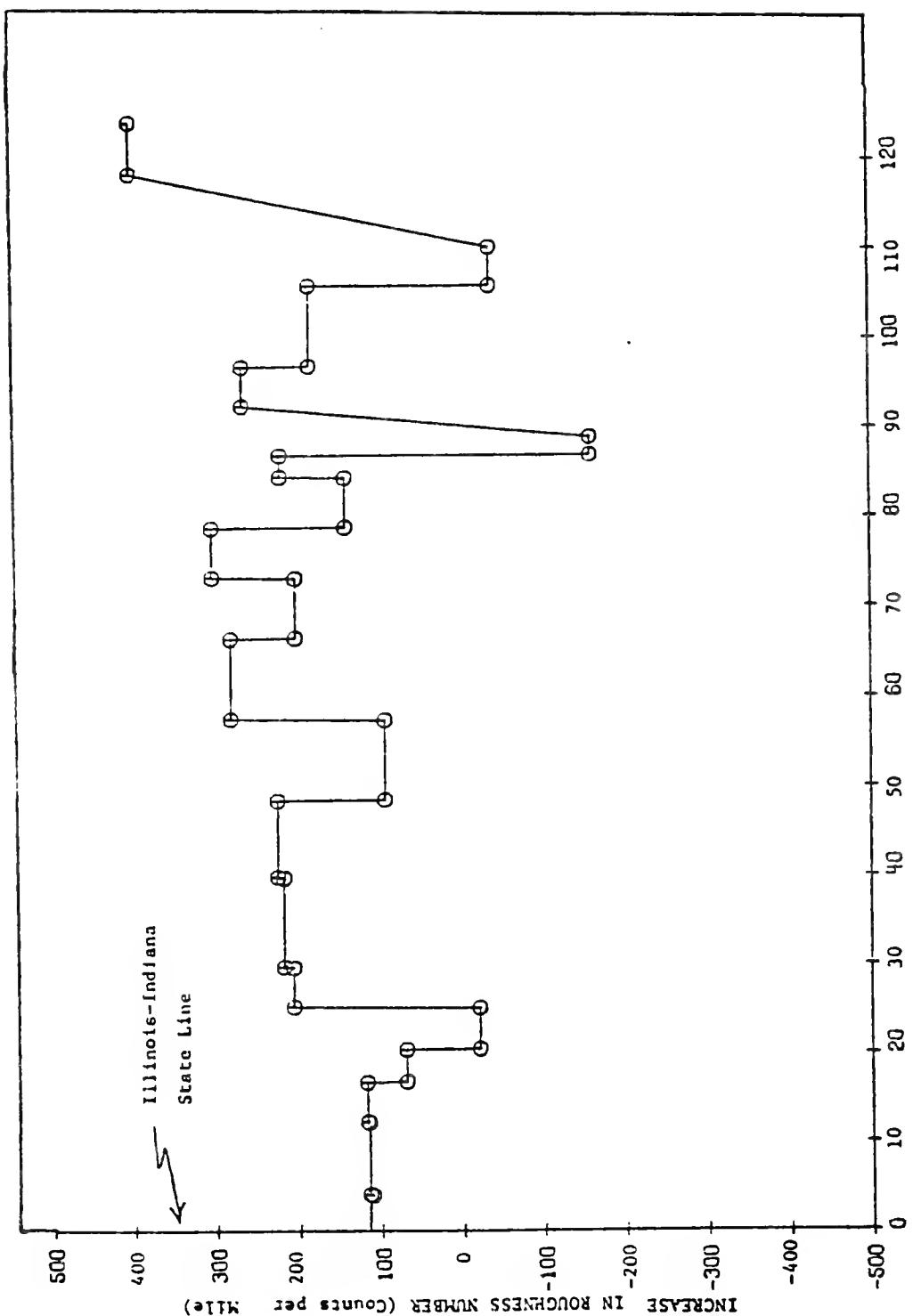


Figure 2. Increase in Roughness Number (1981-1979) vs. Milepost Number for I-64 East (Indiana).

of 400 counts per mile which is at least 150 counts higher than the average increase in roughness experienced by the remaining 120 miles along this route.

It should be realized that these graphs can only be used during the initial stages of any pavement management process to identify those highway contract sections (or miles) which are consistently above or below a pre-determined trigger value associated with each performance factor being considered. To determine the proportion of miles (or contract sections) that can be rehabilitated during a given period of time, an optimization model must be formulated which best suits the needs of the highway agency in question.

It can be argued that a complete pavement management program should encompass both the graphical method during the initial stages to identify the deficient sections and the optimization model to improve cost-effectively the overall condition of the pavement network.

Development of Equivalent Performance Indices

The equivalent performance index (EPI) is an index from 0 to 100 used to represent the effect of each of the performance factors considered. The development of the EPI is based primarily upon the cumulative distribution of each of the performance factors being considered.

The purpose of developing the EPI was to have an equivalent unit of measurement which can be effectively used to compare all performance factors at the same level. The Equivalent Performance Curves developed for roughness and increase in roughness for the interstate and the secondary system for flexible, jointed reinforced, and continuously reinforced concrete pavements are shown in Figures 3 through 7.

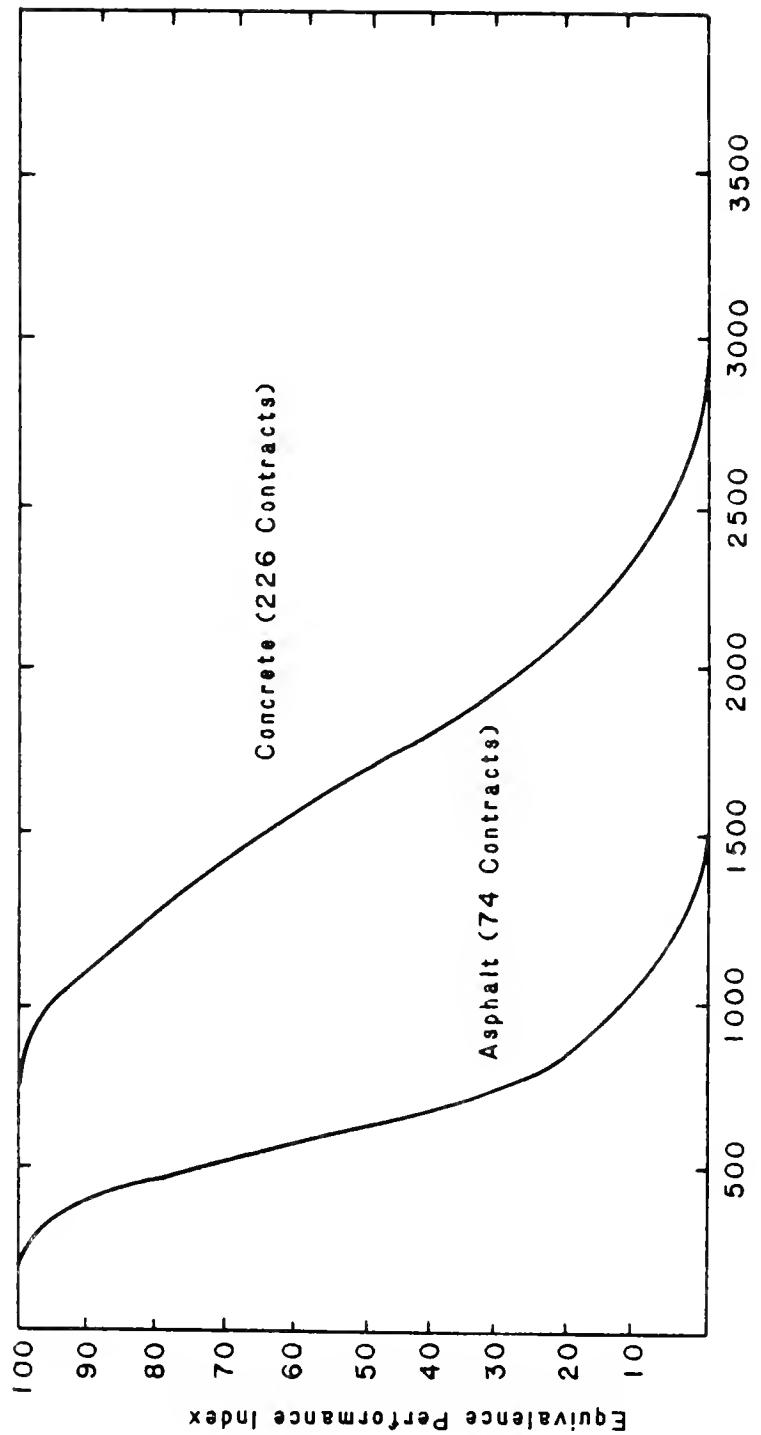


Figure 3. Roughness Number Equivalence Performance Index (EPI) for the Interstate System.

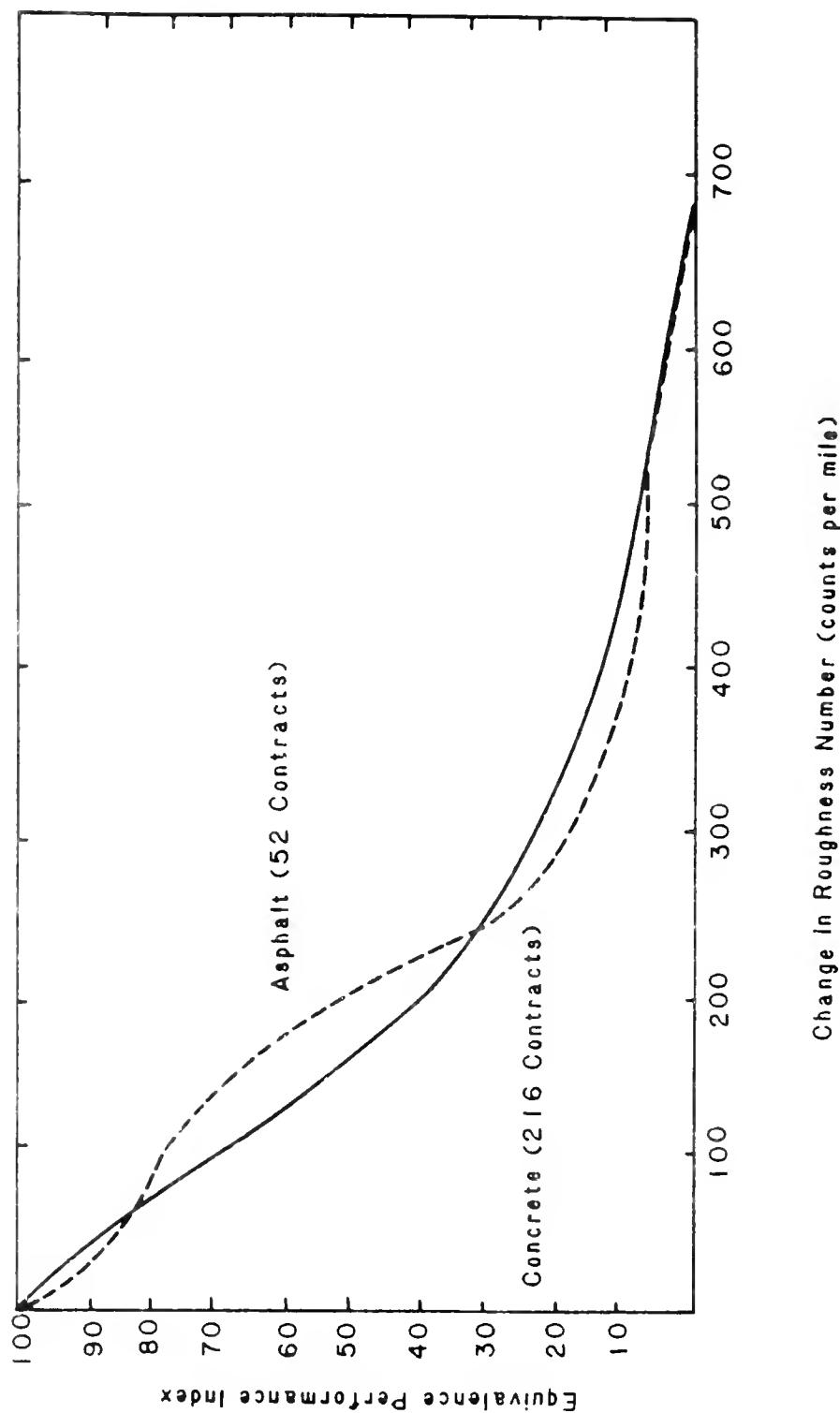


Figure 4. Equivalence Performance Index (EPI) for Change in Roughness Number for the Interstate System.

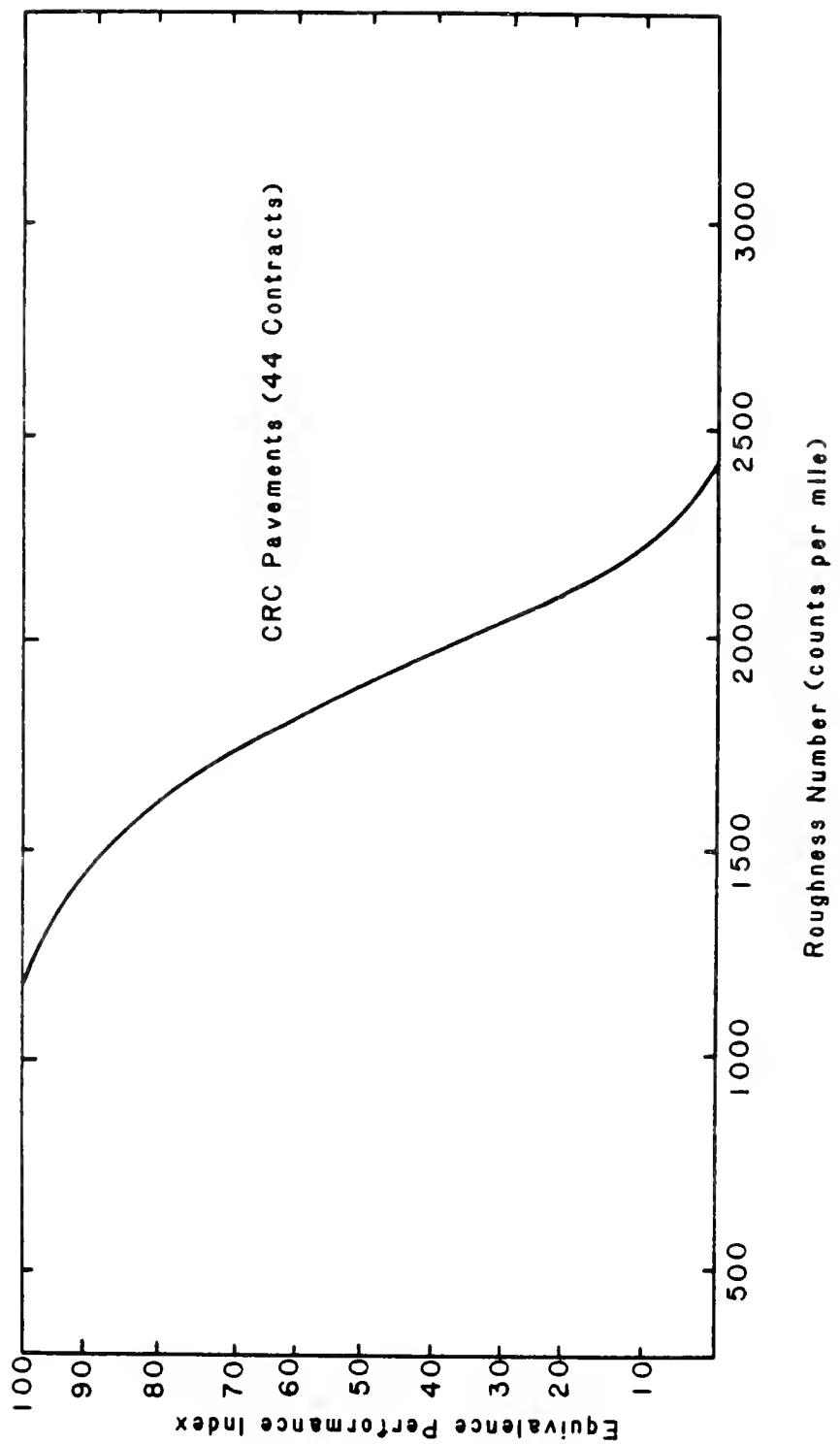


Figure 5. Equivalence Performance Curve for Roughness Number in CRC Pavements.

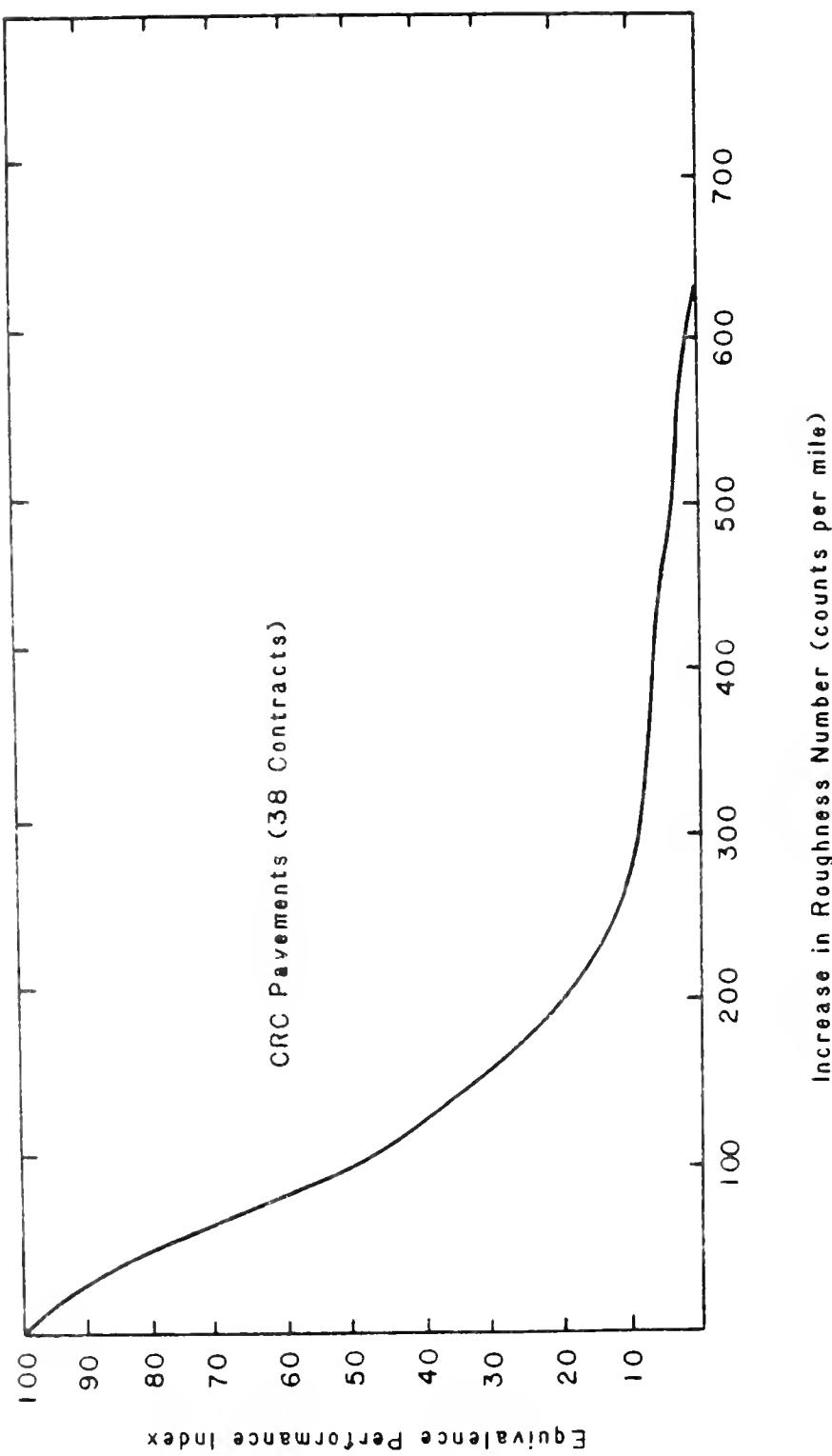


Figure 6.

Equivalence Performance Curve for Increase in Roughness Number
(CRC Pavements).

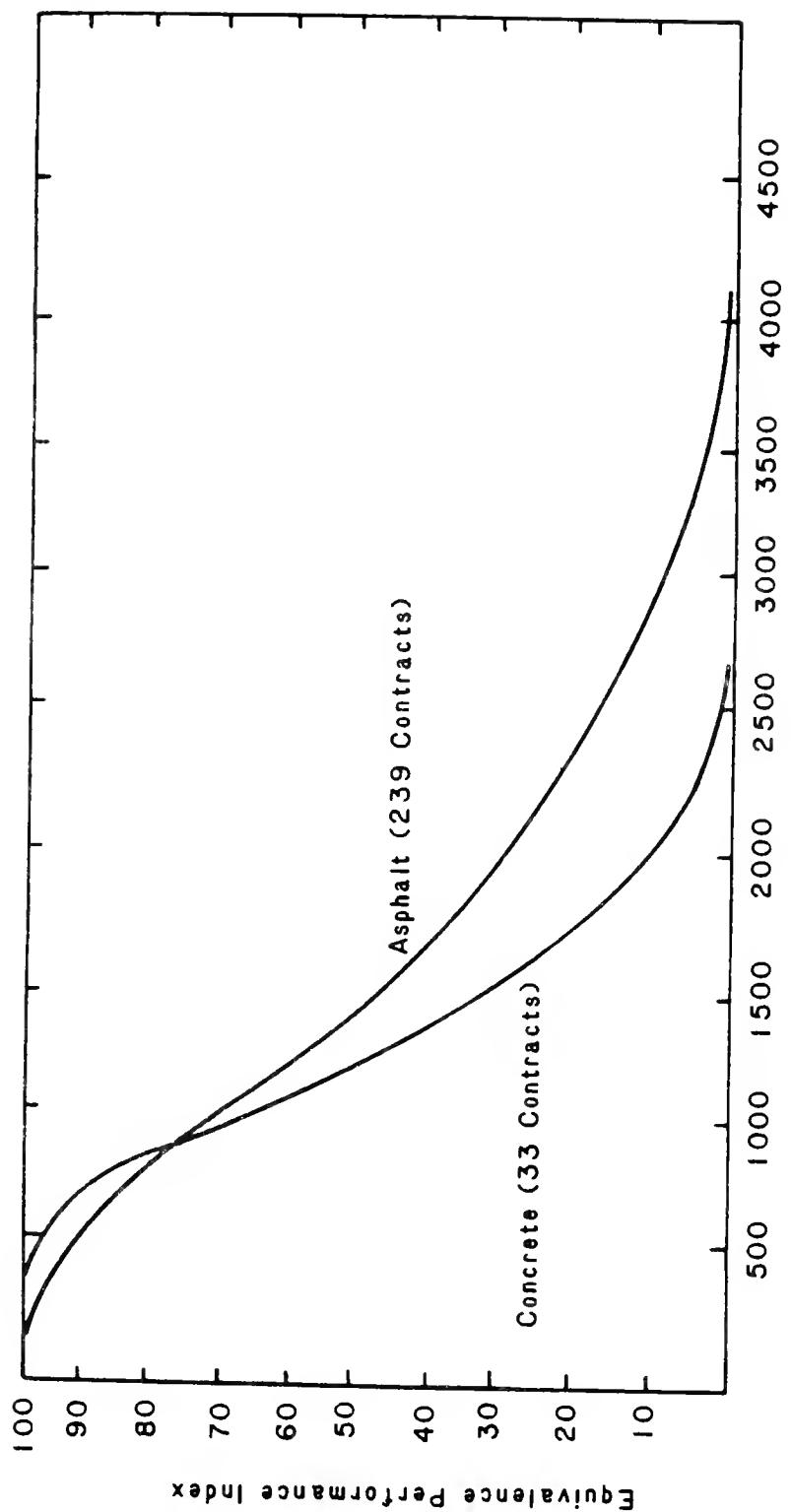


Figure 7. Roughness Number Equivalent Performance Index (EPI) For State Routes.

Each EPI curve was developed from the existing roughness inventory data corresponding to the base year of the analysis period. For example, to construct the equivalent performance curve for jointed reinforced concrete pavements, a total of 226 roughness measurements corresponding to all the concrete contract sections in the interstate system were used. To use the EPI curve, one enters with the roughness number of the particular pavement section, and then reads on the appropriate curve. For example, if the roughness number is 1500 counts per mile on a concrete pavement, from Figure 3 the EPI is found to be approximately 60 on a scale from 0 to 100. Similarly, to use the EPI curve for increase in roughness number one enters with the roughness increment obtained from two consecutive years. For example, a roughness increment of 200 counts per mile on a concrete pavement in a state route would mean an EPI of approximately 40, as indicated in Figure 7.

Importance of Weighing Performance Factors

If each EPI curve is analyzed individually, it can be helpful in establishing priorities as to which pavement sections are in need of maintenance (if EPI is below a pre-determined value), what type of failure is present, and also to what extent the distress has progressed. However, in order to obtain an indication of the overall condition of the stretch of road in question and to gain insight as to the most efficient form of rehabilitation to pursue, the factors must be analyzed collectively as well as individually. The interaction between these factors plays a major role in determining the type of maintenance strategy required. In other words, if a pavement section is not rehabilitated within a certain period of time, a present pavement distress may lead the pavement section to deteriorate to a higher level that a major reconstruction would be necessary.

PAVEMENT CONDITION SURVEYS

Two pavement condition surveys were conducted. The first condition survey was performed on pavement sections located within the interstate system and previously classified by the IDOH as "poor" sections. The second survey was on pavement sections located within the Crawfordsville District to take into account the different distresses present on sections with different traffic distributions and different design criteria as compared to interstate pavements.

Interstate Condition Survey

Two rating forms were developed by IDOH for the interstate condition survey to rate flexible and rigid pavements. The survey was performed on only those concrete pavement sections with a roughness number greater than 2000 and on asphalt pavements with a roughness number greater than 1400 counts per mile. These trigger values were established by a previous research project sponsored by the Joint Highway Research Project on pavement evaluation [4,5]. For each mile of a contract pavement section exceeding the above trigger values, a 200 foot long section was chosen at random as a sample section using a table of random numbers. For example, if a particular contract section was 5 miles long, 5 ratings were performed on this contract section.

If the contract section contained dual lanes, the 200 foot section was chosen in the travel lane. If the contract section had three-lanes, such as I-465, the 200 foot section was chosen in the middle lane. Overlayed pavements were considered as flexible pavements and were rated using the Flexible Pavement Rating Form.

Condition Survey (Federal Aid Primary & Secondary Systems)

The Pavement Condition Index (PCI) rating terms developed by Shahin and Kohn at the U.S. Army Construction Engineering Research Laboratory [8] were used for the condition survey on the Federal-aid Primary and Secondary systems for asphalt and concrete pavements. The PCI approach is based on deduct values which are a function of the type, severity, and density of visible distresses.

The model used to represent the PCI is as follows:

$$PCI = 100 - \left[\sum_{i=1}^p \sum_{j=1}^{m_i} a(T_i, S_j, D_{ij}) \right] F(t, q) \quad (1)$$

where,

PCI = pavement condition index;

a() = a weighted deduct value which depends on the type of distress T_i , severity level S_j , and distress density D_{ij} ;

i = counter for distress types;

j = counter for severity levels;

p = total number of distress types for the pavement type under consideration;

m_i = number of severity levels on the i^{th} type of distress;

$F(t, q)$ = an adjustment function for multiple distresses which vary with the total summed deduct value (t)

and number of deducts (q).

The steps used in this study to determine the PCI were adopted from Reference 8 and summarized below:

1. Divide the contract section into sample units.
2. Inspect each sample unit and determine the types of distress and severity levels associated with each distress. Measure the extent (density) associated with each distress type, severity level and density combination.
3. Compute the total deduct value for each sample unit (TDV).
4. Adjust the total deduct value (CDV) using the adjustment function applicable to each sample unit. The adjustment function is dependent on the number of entries with deduct values over 5 points as well as the total deduct value (TDV).
5. Compute the pavement condition index for each sample unit by subtracting the corrected deduct value from 100 [PCI=100 - CDV].
6. Compute the PCI of the entire contract section by taking the average of the PCI's sample units.
7. Determine the pavement condition rating of the contract section (i.e. Excellent, Very Good, Good, Fair, Poor, Very Poor, Failed).

Asphalt pavements, overlay pavements, and jointed reinforced concrete pavements within the Crawfordsville District were evaluated using the aforementioned procedure.

Correlation Analysis

As a part of this study, it was examined if there was a correlation between the roughness number, pavement condition index, pavement age, and traffic. As it was expected, there was little correlation between pavement condition index and roughness. In addition, the correlation between pavement condition index and current ADT was very low as well. A set of scatter plots

was prepared and these plots indicated that there was no specific pattern between pavement condition, roughness, and pavement age.

Comparison of Rating Procedures

There are several differences between the two procedures used in this study to rate pavements in the Interstate system and the Federal-aid primary and secondary system. First, the PCI method uses an adjustment function which takes into account the different types of distress present in a given pavement section. Therefore, it is not directly proportional to the magnitude and severity of the distresses encountered. For example, there may be a pavement section with just ruts along the wheelpath and no other major distress and the section will be assigned a pavement condition index of about 55. On the other hand, if the rating procedure developed by IDOH is used, the maximum deduction for the same type of distress is just 10 points. Therefore, the pavement condition rating assigned to the same pavement section will be 90 instead of 55.

Another major difference is the fact that the IDOH rating form takes into account the overall riding quality of the pavement section in question in the final rating. The amount deducted from the final rating is a function of the roughness number. For example, if the roughness number of a concrete pavement section is between 2000 and 2250, between 0 and 3 points are deducted from the overall rating. If the roughness number is between 2251 and 2570, between 4 and 7 points are subtracted, up to a roughness number of 3800, in which a maximum of 10 points are deducted.

The PCI method does not take into account the riding quality in terms of the roughness number. Roughness is considered in the PCI method in a rather subjective manner. The final rating, however, is not greatly affected as it

is the case when the IDOH rating procedure is used. This is the main reason why a correlation was encountered when using the IDOH rating forms between pavement condition rating and roughness. Since roughness is already taken into account in the process of computing the pavement condition rating, it is most likely that pavements which show higher levels of roughness have, in a sense, a lower rating.

Discussion on Condition Survey Procedures

The pavement condition index (PCI) and the pavement condition rating (PCR) provided additional information pertaining to the pavement structure which the PCA roadmeter cannot detect. It was shown that no correlation existed between PCI and roughness measurements for pavement sections in the Crawfordsville Highway District. On the other hand, correlations were observed in the Interstate system and regression models showing pavement condition index as a function of roughness, pavement age, and traffic were developed. These correlations, however, are in part due to the nature of the rating procedure used. Furthermore, both methods are quite different in the manner they compute the overall rating for the pavement section in question.

It was not the intent of this research project to conduct an extensive evaluation of pavements in-situ, but to show the importance of an objective measurement of pavement surface condition as a part of the pavement management program envisioned by the state.

PERFORMANCE FUNCTION DEVELOPMENT

The data used to develop the performance function were essentially the

roughness number of the pavement section prior to resurfacing, roughness number after resurfacing, and the type of resurfacing strategy performed on the pavement section in question. In order to perform this task, the following guidelines were followed:

1. All contract sections selected for this task should have roughness measurements within 6 months prior to resurfacing and no later than 6 months it has been resurfaced. This criterion was established since the primary interest is the immediate improvement accomplished by the resurfacing strategy in question and not after the section has been exposed to considerable amount of traffic and weather.
2. All new resurfaced pavement sections should correspond to the same fiscal year so that the cost estimates associated with each resurfacing strategy are for the same year. This way the effect of inflation upon resurfacing costs can be neglected.
3. The cost figures extracted from the construction forms should only be associated with the cost of the pavement structure.

The final construction records related to the pavement resurfacing contracts performed during fiscal years 1981 and 1982 were used to estimate the total resurfacing costs associated with each of the resurfacing activities undertaken during this period. The roughness number for each contract section prior to resurfacing was obtained from the roughness inventory published by the IDOH Research and Training Center. The roughness number just after resurfacing was extracted from the smoothness reports prepared by the IDOH Research and Training Center every year for the smoothness award. The resurfacing contracts considered were those performed on the Interstate system as well as on Federal-aid primary and secondary roads.

Percent Reduction in Roughness

The percent reduction in roughness was calculated for each pavement contract section resurfaced during fiscal year 1982 that met the guidelines

previously discussed. The equation used to calculate percent reduction in roughness is as follows:

$$RN_r = \frac{(RN_b - RN_a)}{RN_b} * 100 \quad (2)$$

where,

RN_r = percent reduction in roughness number after contract section has been resurfaced;

RN_b = roughness number prior to resurfacing;

RN_a = roughness number after resurfacing.

The percent reduction in roughness number and the change in roughness number were then plotted against the cost per mile associated with each pavement section in order to check whether or not there was any significant trend. It is important to note that these plots were generated using all contract sections irrespective of the type of surface (i.e. Hot Asphaltic Emulsion (HAE), Hot Asphalt Concrete (HAC), Modified HAC, and so on).

Based on these plots the following observations were made:

1. Although there was no significant statistical relationship, an overall increasing trend in pavement resurfacing cost could be noted with increasing percent reduction in roughness.
2. No significant statistical relationship could be observed between pavement resurfacing cost and change in roughness number for pavement sections resurfaced in 1982.

In order to develop the performance function, all contract sections were further grouped according to the resurfacing activities most commonly used in Indiana during FY 1982. The grouping was done primarily to minimize the variance among similar homogeneous resurfaced sections. The mean percent reduction in roughness number for each resurfacing group was plotted against the corresponding resurfacing activity in terms of overlay thickness as shown in Figure 8. The performance function model corresponding to these data sets is shown below:

$$\% \text{ Red} = 61.35 * T^{0.26} \quad (3)$$
$$R^2 = 0.83$$

where,

% Red = Reduction in Roughness Number;

T = Overlay Thickness, inches.

It should be noted that this model is applicable only within the range of thicknesses shown in Figure 8. Any attempt to apply the model above or below this range might give unrealistic results. For example, if the model is applied to a pavement section which has been resurfaced with an equivalent thickness of 5 inches, the percent reduction in roughness number using the model would be 93.22 percent and for 6 inches it would go as high as 97.75 percent. These percent reduction values might be unrealistic in many cases. Even the newly resurfaced pavements have a certain level of roughness, somewhere between 300 and 550 counts per mile.

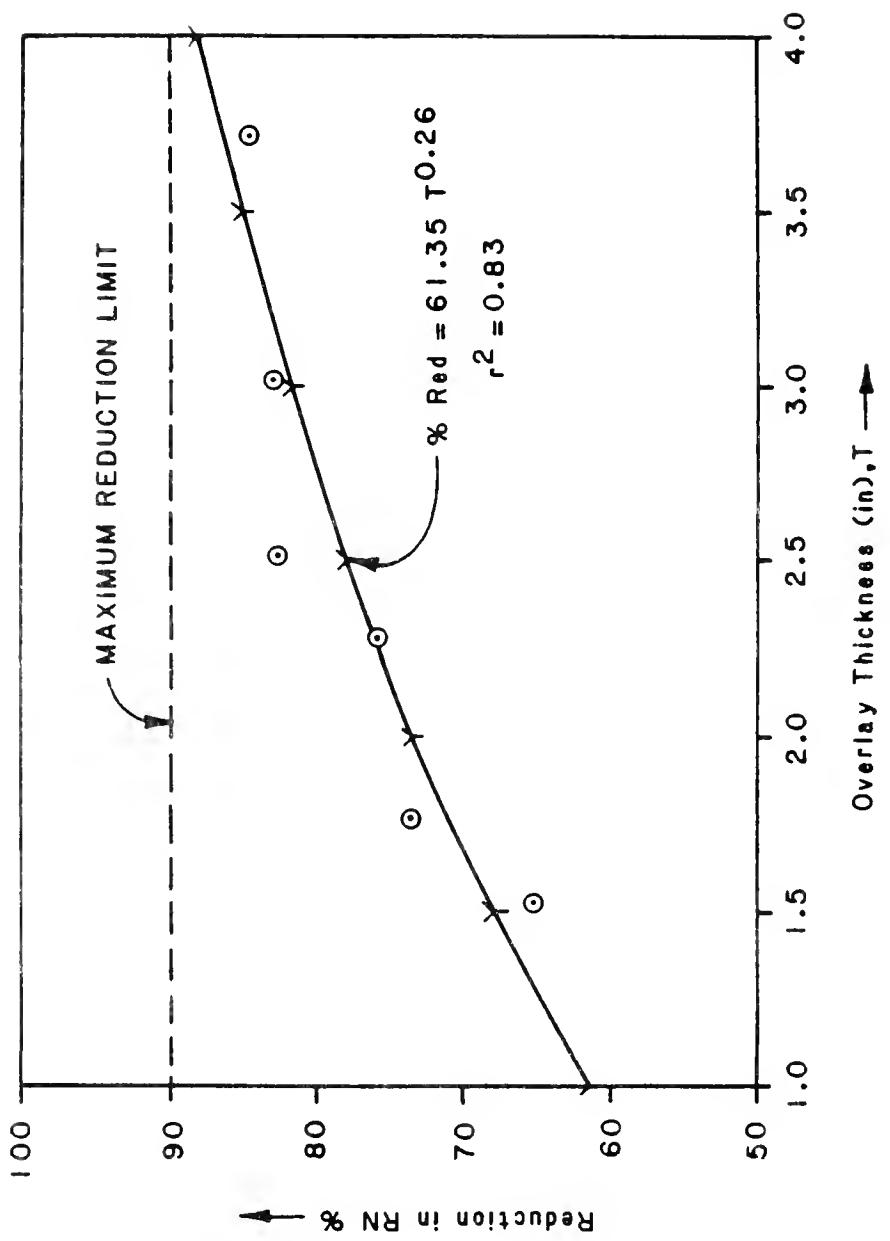


Figure 8. Relationship Between Reduction in Roughness
and Required Overlay Thickness.

Figure 8.

Effect of Resurfacing on Roughness Number

Figures 9 and 10 show the distribution of roughness number for pavement sections resurfaced during 1981 and 1982, respectively. From these figures it can be noted that roughness number values after resurfacing follow a multi-model distribution. In 1982, for example, the first part of the distribution starts at 100 counts per mile and goes to approximately 800. The second part of the distribution starts at about 800 and goes to 1800 counts per mile. The reason behind this form of distributions is that the roughness number after resurfacing is dependent on the roughness prior to resurfacing as well as on the resurfacing strategy adopted. For example, if a pavement section has a very high roughness number, say 4500, and after being resurfaced the roughness is reduced about 77 percent, the new roughness number will probably still be over 1000 counts per mile.

DEVELOPMENT AND APPLICATION OF OPTIMIZATION MODELS

Two model formulations were considered in this study. The first formulation, referred in this study as the contract section worth model, uses the weighed reduction in pavement distress over a five year period as the measure of effectiveness. The second model formulation, referred in this study as the roughness reduction model, uses the total reduction in roughness number as the measure of effectiveness. Trigger values associated with asphalt and concrete pavements were used to identify sections with high roughness number, and only sections with high roughness number were included in the optimization model.

Methodology Description - Contract Section Worth Model

The methodology used for identifying and selecting deficient pavement sections at the beginning of the analysis period is summarized below:

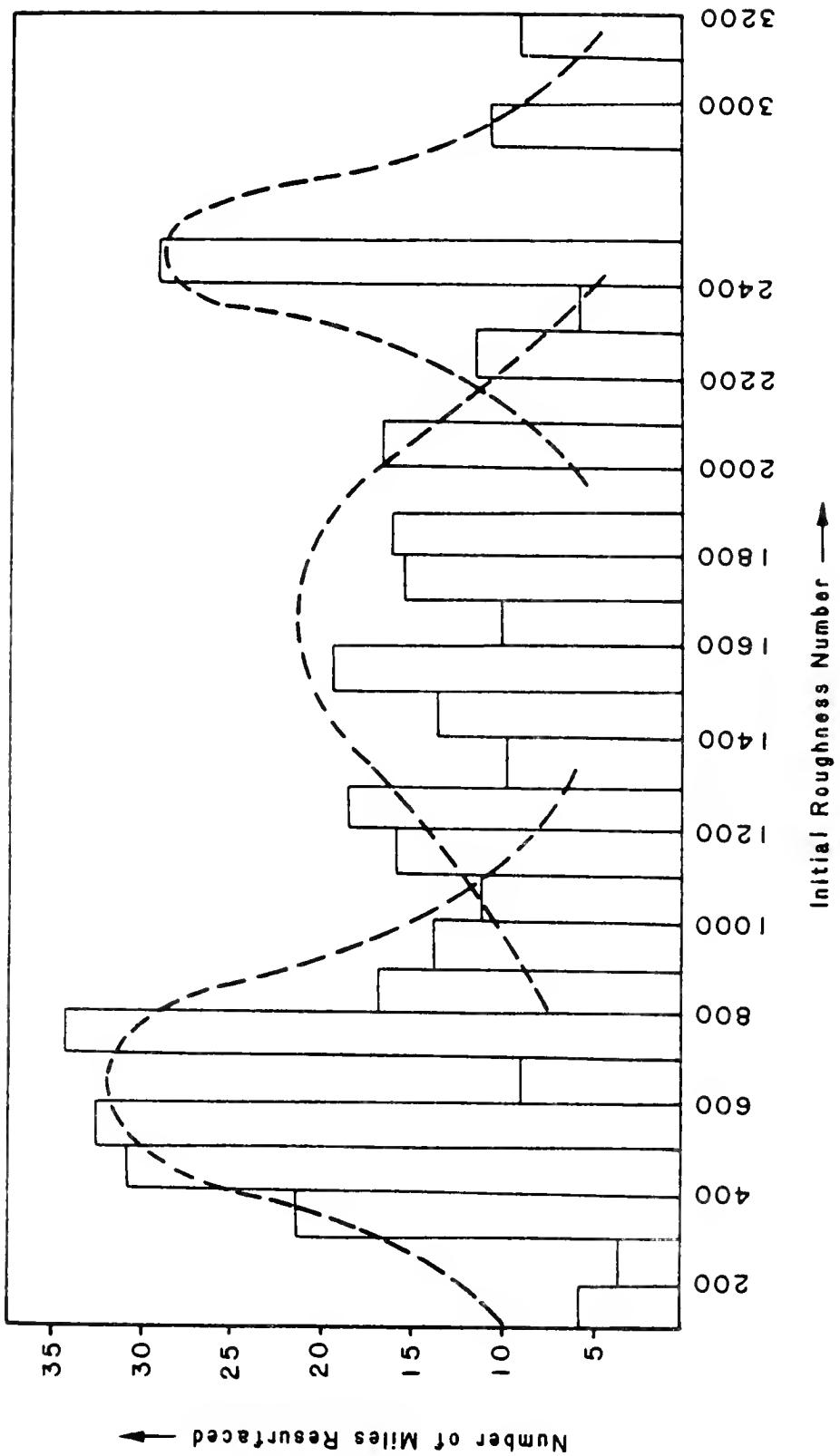


Figure 9. Distribution of Roughness Number Measured
Just After Resurfacing in 1981.

Figure 9.

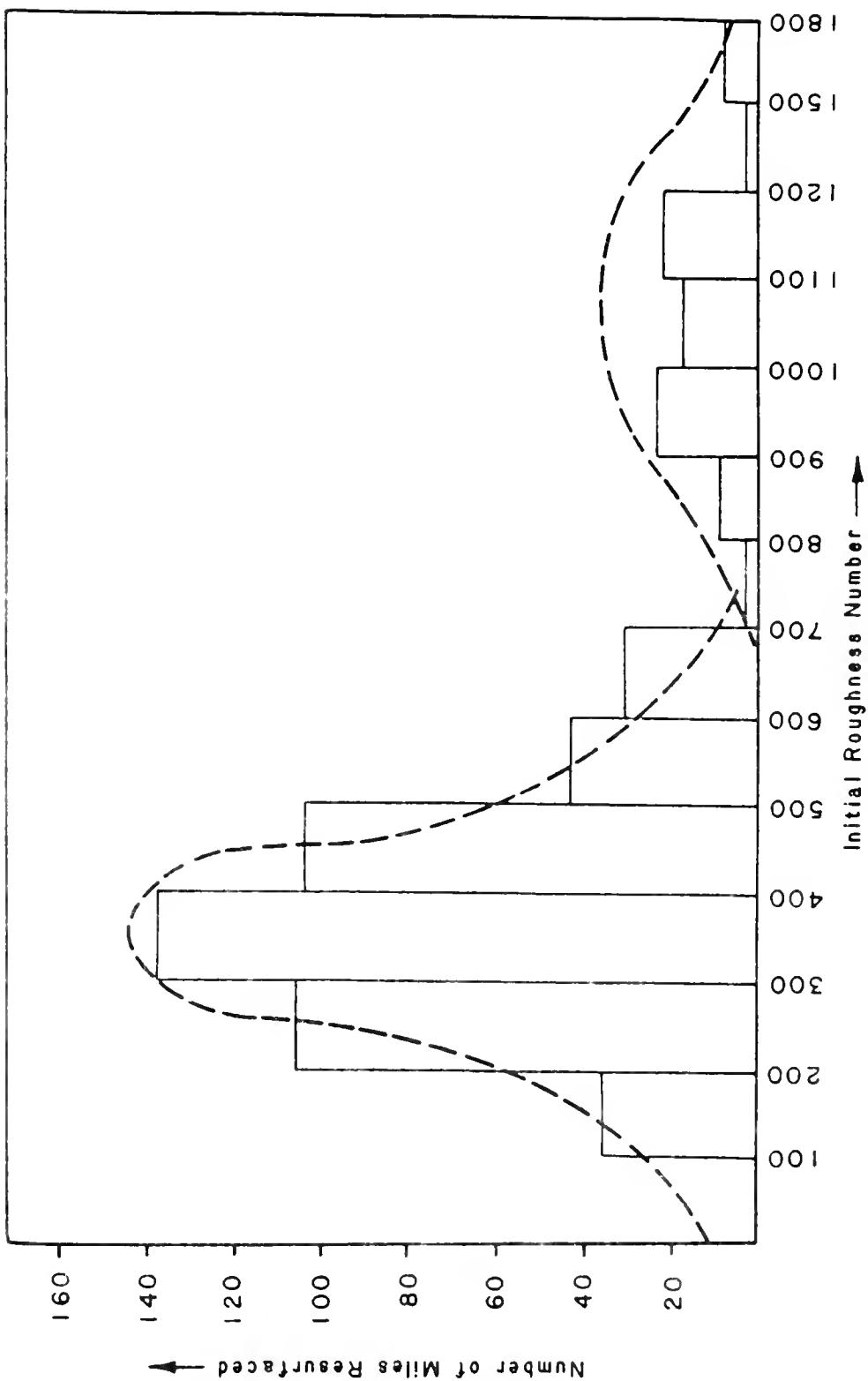


Figure 10. Distribution of Roughness Number Measured Just
After Resurfacing in 1982.

Figure 10.

1. Pavement sections were selected by contract section and classified into two major types of pavements, namely asphalt (includes conventional pavements, full-depth, and overlayed pavements) and concrete (includes JRCP, CRCP, JPCP) pavements.
2. Asphalt pavement sections with a roughness number greater than 1400 counts per mile and concrete pavement sections with roughness number greater than 2000 counts per mile were identified and selected for the pavement condition survey.
3. Contract sections already identified as being rough were further divided into one-mile sections and the pavement condition rating was determined for each section using the rating procedure developed by IDOH for this purpose.
4. An average pavement condition rating was then computed for the entire contract section.
5. Other necessary performance data pertaining to these pavement sections were then obtained from the IDOH Research & Training Center. These included roughness number during the last four years, pavement age, pavement type, directional ADT, and contract length.
6. Performance factors which depend upon the above parameters were then computed. These included weighed directional ADT for each pavement section, change in roughness number between any two years, and cumulative ADT since the section was opened to traffic.
7. Equivalent performance curves were then used to transform the aforementioned performance indicators into an equivalent scale from 0 to 100,

0 corresponding to very poor condition, and 100 corresponding to excellent condition.

8. Each performance factor was then weighed according to its relative importance among the factors being considered with the sum of the assigned weights equal to unity.
9. Resurfacing activities were then assigned to each contract section selected for the optimization problem based on the current ADT of the facility. A total of three resurfacing activities out of a possible seven were assigned to each pavement section.
10. Percent reduction in pavement roughness associated with the resurfacing activities assigned to each contract section was then computed using the performance function model.
11. Traffic growth factor associated with each pavement section was estimated.
12. Average routine maintenance costs expected during the next five years for the resurfacing strategies considered were input to the program.
13. Unit cost information associated with each resurfacing activity was then used along with the length of each contract section to compute the resurfacing costs of each pavement section considered in the formulation.
14. Budget estimates obtained from IDOH Planning Division for the current year as well as for the last four years were then used to estimate the expected budget for the next four years of the analysis period. This information was input to the optimization formulation.

15. The objective function and constraint coefficients were then determined.
16. The zero-one integer programming technique was then used to run the proposed formulation. The pavement contract sections selected for resurfacing by the optimization program during each year of the analysis period were then tabulated.

The procedure followed in selecting additional pavement sections to be considered after the first year of the analysis period is summarized below:

1. The roughness inventory data corresponding to years 1979 through 1982 were obtained from the IDOH Research and Training Center for each interstate route.
2. Summary tables containing performance information of the pavement section as well as the roughness numbers for the last four years were generated by interstate route and the information was tabulated by contract section. These included the length of the pavement section, pavement type and surface, directional ADT, pavement age, cumulative ADT, and the roughness numbers corresponding to the last four years.
3. All pavement sections which did not have roughness number measured in each of the last four years were disregarded.
4. All pavement sections which were resurfaced within the last three years were also disregarded since it was assumed that any resurfacing performed in the interstate highway system, irrespective of the thickness of the surface course, would perform satisfactorily for at least during the five years considered in this analysis.

5. Regression equations were then developed for each interstate route and pavement type combination using the roughness number measurements for two years. The equation to estimate roughness number for a particular year was developed as a function of the roughness number of the preceding years by interpolating the results of the regression analysis.
6. The regression coefficients applicable to each interstate route and pavement type were then used to predict the roughness number for subsequent years.
7. All those pavement sections which exceeded the roughness limits associated with each type of pavement during any of these four years were then input to the optimization model in the year in which the roughness number was exceeded.
8. All other performance information associated with these pavement sections was then obtained in the same manner as for the sections selected during the first year of the analysis period.

Model Formulation

The optimization model referred in this study as the contract section worth model, uses the weighed reduction in pavement distress over a five year period as the measure of effectiveness. The objective function coefficients for the contract section worth model were computed by multiplying the following three factors:

1. Contract Section Worth (CSW)
2. Percent reduction in pavement roughness caused by a particular resurfacing type.

3. Traffic growth rate and rate of increase in roughness for each contract section.

The worth of each contract section CSW_i was calculated as follows:

$$CSW_i = TADT_i [(1-RNEPI_i) (WRN) + (1-\Delta RNEPI_i) (\Delta WRN) + (1-AGEEPI_i) (WAGE) + (1-PCI_i) (WPCI)] \quad (4)$$

where,

CSW_i = worth of contract section i;

$TADT_i$ = accumulated average daily traffic in one direction
for contract section i in veh/day;

$RNEPI_i$ = roughness number equivalent performance index for
contract section i ($0 < RNEPI < 100$);

WRN = roughness number's relative weight ($0 < WRN < 1$);

$\Delta RNEPI_i$ = the equivalent performance index for change in
roughness for contract section i, ($0 < \Delta RNEPI < 100$);

ΔWRN = relative weight of change in roughness number,
($0 < \Delta WRN < 1$);

$AGEEPI_i$ = pavement age equivalent performance index for
contract section i;

$WAGE$ = relative weight assigned to pavement age, ($0 < WAGE < 1$);

PCI_i = pavement condition index for contract section i,
($0 < PCI < 100$);

$WPCI$ = relative weight assigned to pavement condition index,
($0 < WPCI < 1$).

The average daily traffic of each contract section was obtained from the latest traffic flow maps published by the IDOH Planning Division. The total accumulated ADT of each contract section was computed using the directional ADT and the equation is shown below:

$$\text{Accumulated ADT} = \frac{\text{ADT}_0 \times 365}{\log_e(1+g)} \left[(1+g)^{\text{age}} - 1 \right] \quad (5)$$

where,

$$\text{ADT}_0 = \text{ADT when opened to traffic} = \frac{\text{ADT}_p}{(1+g)^{\text{age}}};$$

g = annual traffic growth rate;

age = pavement age (present year - year opened to traffic);

ADT_p = present ADT.

The equivalent performance indices for roughness, change in roughness, and pavement age for each contract section were estimated after interpolating the appropriate performance curves described earlier in the report.

The relative weights for roughness, change in roughness number, pavement age, and pavement condition index were estimated in consultation with members of the IDOH Pavement Management Task Force Committee. These weights reflect the relative importance of each of the performance factors considered in the formulation. The contract section worth model is shown below:

$$\text{Max } Z = \sum_{i=1}^n \sum_{j \in A_i} \sum_{k=1}^{n_{\text{year}}} G_{ik} \text{CSW}_i \text{RED}_j x_{ijk} \quad (6)$$

subject to:

$$\sum_{i=1}^n \sum_{j \in A_i} IF_k \left[L_i TRC_j \begin{bmatrix} x_{ijk} & -x_{ijk-1} \end{bmatrix} + L_i RMC_j x_{ijk} \right] \leq B_k \quad (7)$$

$$\sum_{j \in A_i} x_{ijk} \leq 1 \quad \text{for all } i \text{ and } k \quad (8)$$

$$\sum_{j \in A_i} x_{ijk} > x_{ijk-1} \quad \text{for all } i, k \text{ and } j \in A_i \quad (9)$$

where,

RED_j = percent reduction in pavement roughness if resurfacing activity j is selected;

x_{ijk} = 1 if contract section i receives resurfacing activity j in year k , 0 otherwise;

L_i = length of contract section i (miles);

TRC_j = total resurfacing cost associated with activity j in 1982-83 dollars per center-line mile;

RMC_j = annual routine maintenance cost associated with resurfacing activity j in dollars per center-line mile;

$j \in A_i$ = resurfacing activity j which is one of the set of three feasible alternatives for pavement contract

section i , A_i ;

B_k = available budget for the k^{th} year;

G_{ik} = growth factor for deterioration of contract section i in the k^{th} year, $RN(k)/RN(k-1)$;

IF_k = inflation factor, $(1+i)^k$;

i = interest rate used, 6 percent;

n = total number of deficient pavement contract sections;

nyear = number of years in analysis period.

Equation 6 states that the product of the contract section worth and percent reduction in pavement roughness should be maximized. An additional parameter, G_{ik} , is included as part of the objective function coefficient to take into account the annual deterioration rate associated with each contract section. This factor was computed as the ratio of the present roughness number and the roughness number of the previous year. If the growth factor computed with the above equation was found to be less than unity for any particular pavement section, the factor was then reset to one. The primary reason for setting a lower bound on this factor is because each pavement section entered into the model was assumed to be a truly defective section; therefore, this section could be expected to continue to deteriorate as it passed from one year to another.

Equation 7 represents the constraint that the total cost of all rehabilitation projects to be implemented must not exceed the available resurfacing program budget for each of the fiscal years in the analysis period.

Equation 8 indicates that no more than one rehabilitation project can be selected among alternative project types for a contract section in a given year.

Equation 9 assures that if a rehabilitation project has already been implemented in a previous year, only the routine maintenance task of that particular resurfacing activity (if any) will be performed in the current year. For example, if a 4" overlay had been applied to contract section RS-8001 dur-

ing 1983, only routine maintenance would be performed on this section in 1984 and during the rest of the analysis period. However, it is important to note that the routine maintenance cost associated with a 4" overlay is not necessarily the same as with a 3" or 2" overlay. This is the main reason for introducing this constraint into the model.

In addition, Equations 8 and 9 imply that, at most, only one rehabilitation project is selected for each contract section during the analysis period.

The parameter used in the objective function to represent the percent reduction in pavement roughness, RED_j , was predicted using the performance function model described earlier in the report.

Application of the CSW Model

To illustrate the application of the multi-year optimization model, the Indiana interstate highway system was used. A total of seventy contract sections were initially selected and additional forty-eight sections were included for subsequent years using the roughness prediction models developed for each interstate route and pavement type. The alternative resurfacing strategies considered are presented in Table 1.

The LINDO (Linear Interactive and Discrete Optimizer) computer package was selected to run the optimization program for this study since it is capable to handle a sufficiently large scale problem [6,7].

Optimal Resurfacing Program

Table 2 presents the results obtained from the application of the optimization model. The contract sections that were selected for resurfacing under

Table 1. Percent Reductions in Roughness, Initial Resurfacing Costs, and Annual Routine Maintenance Costs of Alternate Resurfacing Activities

Resurfacing Activity (in) [*]	% Reduction Roughness	Resurfacing Cost (\$/center-line mile)	Routine Maintenance Cost (\$/center-line mile)
a (1")	.6135	310,000	900
b (1.5")	.6817	345,000	765
c (2.0")	.7347	371,000	635
d (2.5")	.7785	393,000	500
e (3.0")	.8163	412,000	365
f (3.5")	.8497	429,000	235
g (4.0")	.8797	445,000	105

*The resurfacing activity expressed in lbs. per square yard is shown below:

$$\begin{aligned}
 a &= 90 \text{ lbs./sys} \\
 b &= 175 \text{ lbs./sys} \\
 c &= 70 + 135 \text{ lbs./sys} \\
 d &= 70 + 220 \text{ lbs./sys} \\
 e &= 110 + 220 \text{ lbs./sys} \\
 f &= 70 + 135 + 175 \text{ lbs./sys} \\
 g &= 70 + 175 + 175 \text{ lbs./sys}
 \end{aligned}$$

Table 2. Results from Contract Section Worth Model for Budget Scenario 2: Interstate Highway System

Section (coded)	Calendar Year					Resurfacing Activity +	Section Length
	1982	1983	1984	1985	1986		
1			*			e	4.6
2						n/s	5.8
3						n/s	7.1
4			*			c	3.7
5				*	*	c	6.1
6					*	c	6.4
7		*				e	5.1
8				*		c	6.0
9			*			c	3.7
10			*			c	4.1
11			*			c	4.4
12				*		n/s	3.6
13			*			c	4.4
14		*				c	3.7
15				*		c	5.1
16			*			c	6.4
17					*	c	6.1
18			*			c	3.7
19	*					e	4.5
20		*				c	2.9
21		*				c	6.2
22				*		c	7.8
23		*				e	5.3
24			*	*		c	4.1

Table 2. Results from Contract Section Worth Model for Budget Scenario 2: Interstate Highway System (Continued)

Section (coded)	Calendar Year					Resurfacing Activity	Section Length
	1982	1983	1984	1985	1986	*	
25						*	c 5.7
26							n/s 5.2
27						*	a 4.4
28						*	a 5.5
29						*	c 4.4
30			*				e 5.8
31	*						e 2.0
32							n/s 4.8
33				*			e 7.3
34	*					.	e 0.7
35						*	e 6.6
36	*						c 3.5
37							n/s 5.3
38				*			e 6.6
39				*			c 2.7
40					*		c 5.8
41				*			c 2.7
42	*						e 3.2
43					*		e 5.8
44				*			e 4.0
45				*			e 4.4
46	*						c 2.2
47		*					c 3.7
48	*						c 2.7

Table 2. Results from Contract Section Worth Model for Budget Scenario 2: Interstate Highway System (Continued)

Section (coded)	Calendar Year					Resurfacing Activity ⁺	Section Length
	1982	1983	1984	1985	1986		
49				*		c	5.3
50				*		c	3.1
51			*			c	5.3
52					*	c	4.2
53		*				c	1.7
54	*					e	4.4
55					*	e	4.0
56				*		e	5.8
57	*					e	4.5
58		*				e	6.4
59		*				e	5.3
60				*		c	9.2
61			*			c	6.4
62		*				c	6.9
63				*		c	6.4
64	*					c	0.4
65			*			n/s	9.2
66		*				c	5.3
67		*				e	6.4
68	*					e	4.5
69	*					g	2.5
70	*					e	3.7
71			*		*	e	1.6
72		*				e	3.2

Table 2. Results from Contract Section Worth Model for Budget Scenario 2: Interstate Highway System (Continued)

Section (coded)	Calendar Year					Resurfacing Activity ⁺	Section Length
	1982	1983	1984	1985	1986		
73				*		e	1.2
74						n/s	5.5
75						n/s	4.4
76					*	c	5.2
77					*	e	1.7
78					*	c	3.3
79				*		e	1.4
80			*			e	2.5
81		.			*	e	1.4
82					*	e	5.4
83					*	c	3.6
84					*	c	5.1
85					*	c	3.7
86					*	c	4.1
87			*			e	4.0
88				*		e	4.4
89					*	c	3.6
90					*	a	3.7
91					*	c	4.1
92			*			e	4.0
93				*		e	3.3
94					*	e	6.6
95			*			e	5.8
96		*				e	0.7

Table 2. Results from Contract Section Worth Model for Budget Scenario 2: Interstate Highway System (Continued)

Section (coded)	Calendar Year					Resurfacing Activity ⁺	Section Length
	1982	1983	1984	1985	1986		
97				*		e	7.3
98					*	e	3.7
99					*	c	6.6
100				*		c	4.8
101					*	e	0.7
102					*	e	7.3
103					*	c	3.7
104						n/s	6.3
105						n/s	5.3
106						n/s	6.0
107						n/s	5.8
108						n/s	5.4
109				*		c	3.5
110						n/s	7.5
111					*	c	5.8
112					*	g	2.5
113					*	e	3.2
114				*		e	1.3
115			*			e	2.9
116					*	g	2.5
117					*	e	3.4
118				*		g	1.2
Contracts	13	15	22	22	31	103	87.3
Miles	38.3	68.6	92.5	111	128.8	439.7	83.5

Note: * - indicates the year the sections would be resurfaced
 + - see Table 7.5 for resurfacing activity code
 n/s - contract section not selected for resurfacing

a pre-established budget scenario are marked with the symbol `*' in the optimal year selected by the optimization algorithm.

The type of resurfacing activity selected by the model, the total optimal number of miles resurfaced in each year as well as the total number of contracts are also included in the Table.

Optimal Number of Miles Resurfaced

Figure 11 shows the sequence of pavement resurfacing miles for a particular budget scenario. Based on this Figure, it can be noted that at the beginning of the analysis period about 340 center-line miles were considered deficient and at the end of the five year period only 87.2 miles (216.0 - 128.8) were considered deficient and carried over to calendar year 1987. The information of this type can also be used to monitor how many center-line miles will be optimally assigned for resurfacing in any calendar year for any budget scenario considered.

Effect of Alternate Budget Scenarios

In order to investigate the effect of different levels of budget on the effectiveness of resurfacing programs, the model was run with different budget levels as shown in Figure 12.

Using the budget information furnished by IDOH, the total present worth figure of \$187 millions is the approximate budget expected to be allocated to the interstate resurfacing program during the five years considered. Based on this information, Indiana can be expected to resurface about 450 interstate center-line miles of the interstate system during this period of time. This would be equivalent to resurfacing about 85 percent of all the deficient

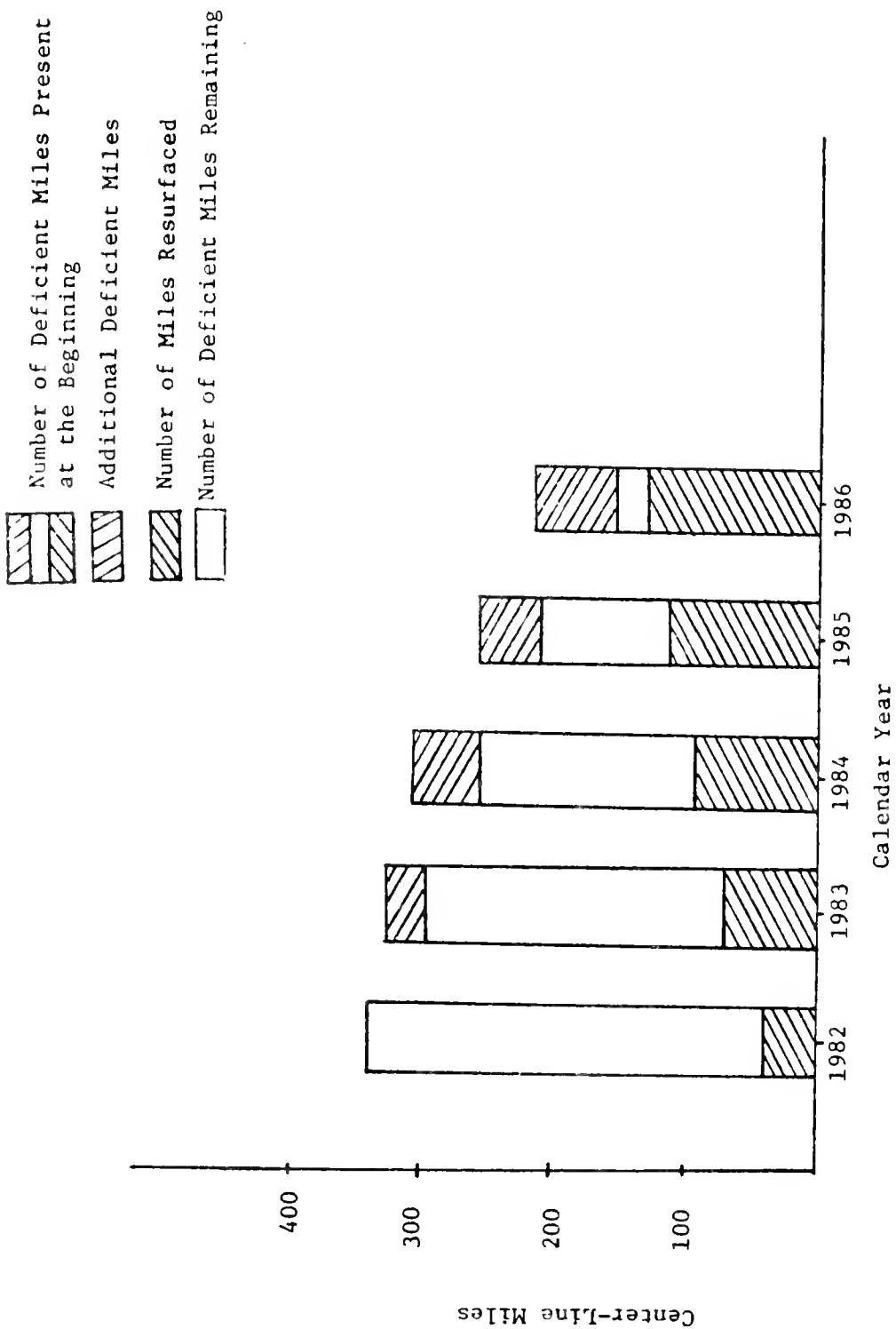


Figure 11. Pavement Resurfacing Mile Sequence Under Budget Scenario 2 - Contract Section Worth Model.

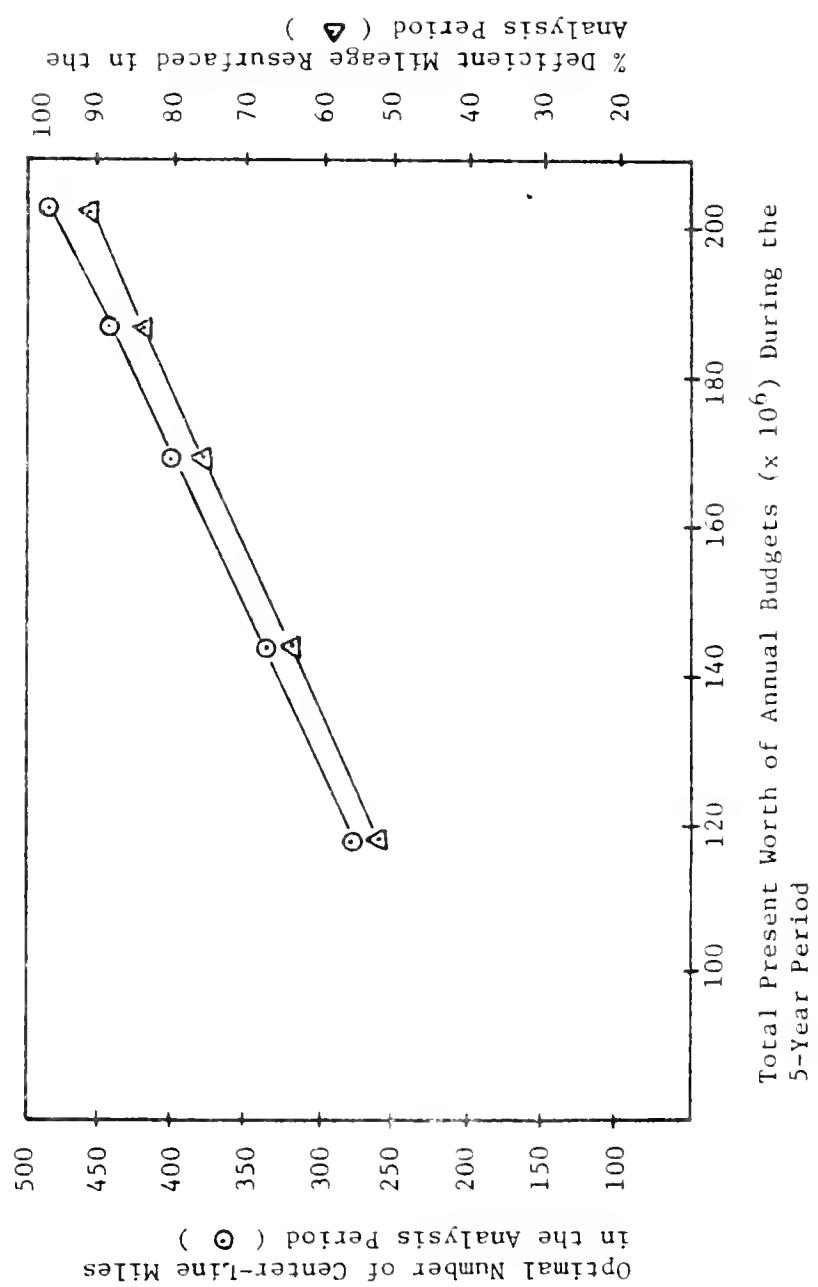


Figure 12. The Effect of Budget Level for Interstate Resurfacing Program Upon the Number of Miles Resurfaced - Contract Section Worth Model.

center-line miles during the five year analysis period. This graph can also be used to determine how many additional center-line miles can be resurfaced to improve optimally the overall pavement condition during the next five years if the budget available for the interstate resurfacing program were increased.

Rate of Resurfacing per Year

Figure 13 shows the rate at which contract sections are selected for resurfacing each year depending upon the budget level considered. It can be noted that the slope for a particular budget level changes from year to year. In addition, the slopes of the budget scenarios are not the same. This fact indicates that the model optimally selects different sets of deficient contract sections depending upon the budget available each year in order to maximize overall reduction in pavement distress.

Cost Summary

Table 3 summarizes the total pavement resurfacing costs (TPRC) and total routine maintenance costs (TRMC) allocated by the model each year of the analysis period. The percent of budget spent in an optimal manner is also shown in the Table.

It can be noted that over 90 percent of the available budget was assigned in an optimal manner during the entire 5-year period. Also, it can be seen that resurfacing activities 'c' and 'e' were the most frequently selected by the optimization routine since 96 out of the 103 contract sections selected for resurfacing were assigned one of these two activities. In most cases, the resurfacing strategy selected by the optimization model was the most expensive of the three feasible rehabilitation strategies pertaining to the pavement

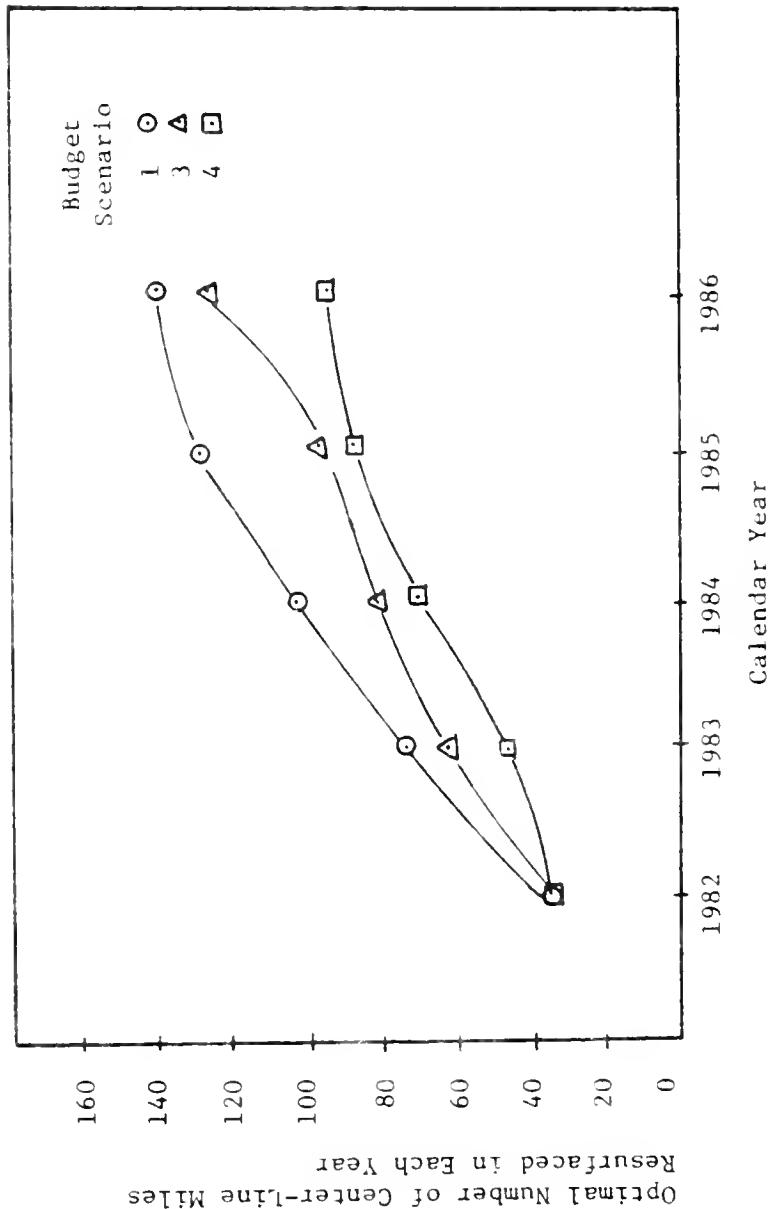


Figure 13. The Effect of Budget Scenarios on the Number of Miles Resurfaced - Contract Section Worth Model.

Table 3. Detailed Summary Under Budget Scenario 2 Using Contract Section Worth Model

Resurf. Strategy (coded)*	Resurf.	Routine Maint. Cost (\$/clm)++	TPRC + TRMC++		TPRC, TRMC ($\times 10^6$) ($\times 10^3$)		TPRC, TRMC ($\times 10^6$) ($\times 10^3$)		TPRC, TRMC ($\times 10^6$) ($\times 10^3$)		TPRC, TRMC ($\times 10^6$) ($\times 10^3$)	
			1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
a	310,000	900										
b	345,000	765	3.46	5.92	11.28	21.69	22.53	38.57	34.99	59.89	32.07	54.89
c	371,000	635										
d	393,000	500	12.01	10.64	17.68	15.67	19.77	17.52	18.88	16.73	25.14	22.27
e	412,000	365										
f	429,000	235	1.18	.28			.64	.15				
g	445,000	105										
Total		16.65	16.84	28.96	37.36	42.94	56.24	53.87	76.61	65.83	94.24	208.25
% Budget Spent (Without TRMC)		97.94		90.5		93.36		89.78		87.78		281.13
% Budget Spent (Including TRMC)		98.04**		90.66**		93.61†		90.11†		88.29†		90.67

Note:

- * TPRC means total pavement resurfacing cost
- ++ TRMC means total routine maintenance cost
- ++ clm means center-line miles
- * refer to Table 1 for resurfacing activity code
- ** includes accumulated routine maintenance costs attributed to pavement sections resurfaced on previous years

section in question. Likewise, it was the resurfacing alternative that contributes most to the objective function value.

Approximately 10 percent of the budget over the five year analysis period was never assigned. It can be recalled that the smallest unit for resurfacing established for this study was the pavement contract section. Therefore, in some cases, during a given calendar year, there may be sufficient money left to resurface only a fraction of a set of contract sections. However, this was not considered in the optimization routine since it is not feasible to resurface only a part of the contract section.

Methodology Description - Roughness Reduction Model

The roughness reduction model was formulated in this study as an alternate model for the IDOH pavement management system. The model, in its present form, uses the present roughness number of each contract section along with the variable that represents the percent reduction in roughness number associated with a particular resurfacing strategy and the rate of increase in roughness number for each contract section to compute the objective function coefficients. The only difference between the contract section worth model and the roughness reduction model is that the contract section worth factor was replaced with the present roughness number in the roughness reduction model. The total reduction in roughness number for each pavement section after the application of a particular resurfacing strategy is the new measure of effectiveness. The objective function for the roughness reduction model is shown below:

$$\text{Max } Z = \sum_{i=1}^n \sum_{j \in A_i} \sum_{k=1}^{n_{\text{year}}} RN_{ik} G_{ik} RED_j x_{ijk} \quad (10)$$

where,

RN_i = present roughness number for contract section i;

G_{ik} = roughness increase rate for contract section i
in the k^{th} year;

RED_j = percent reduction in pavement roughness if
resurfacing activity j is selected;

x_{ijk} = 1 if contract section i receives resurfacing
activity j in year k, 0 otherwise;

nyear = number of years in analysis period;

n = total number of deficient pavement contract sections.

The constraints of the roughness reduction model remain the same as in case of the contract section worth model.

CONCLUSIONS

This research was aimed at the development of a procedure including an optimization routine that can be used by the Indiana Department of Highway in establishing resurfacing priorities under limited financial resources. The data analysis procedure developed in this study identifies contract sections that are in need of rehabilitation. The optimization model then assigns the appropriate resurfacing strategy for rehabilitation of these sections in an optimal manner. The model takes into account future routine maintenance costs once the contract section is chosen for rehabilitation. In its present format, the optimization model is formulated to address a five-year rehabilitation program. However, a short term planning horizon can be incorporated with

relatively minor changes. It should be recognized that the optimization model developed in this study has several limitations which should be considered if it is to be used as a part of Indiana's pavement management program. These limitations are primarily related to the availability of necessary data.

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